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Vertical and horizontal crustal movements in central and northern Italy

P. Baldi[1], G. Casula[2], N. Cenni[1], F. Loddo[2], A. Pesci[2] and M. Bacchetti[1]

[1] *Dipartimento di Fisica, Università di Bologna, Italy*
[2] *Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy*

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ABSTRACT The data from continuous GPS stations located in central and northern Italy, installed with different criteria and planned for scientific or commercial aims, are analyzed to provide the actual crustal movements. The mean velocity of 185 sites have been used to describe both the horizontal and vertical displacement field: the results indicate that the outer part of the Apennine belt moves in a north-eastern direction significantly faster than the inner Tyrrhenian side of the same chain; both Alpine and Apenninic regions show a low uplift, while in the central and eastern sector of the Po Plain the subsidence rate is constant or, in some cases, is decreasing with respect to the values obtained from the last measurements, performed up to 2006 by means of both SAR and leveling techniques. Only the central part of the eastern Po Plain close to the Apennine border (Modena city area) seems to be characterized by an anomalous rate subsidence (15 mm/yr).

Key words: GPS network, velocity field, central and northern Apennines.

1. Introduction

Several continuously-operating GPS stations (CGPS) have been established in the Italian peninsula providing very accurate measurements for scientific purposes, concerning tectonic and geodynamic studies, reference frame definition and atmospheric effects analyses.

Some public institutions (ARPA Piemonte, Regione Abruzzo, Regione Friuli Venezia Giulia, Regione Lombardia and Regione Veneto) and private agencies (ASSOGEO, SOGER) have recently developed CGPS networks (Fig. 1), in order to support mapping activities, rescue and emergency services and real-time positioning (VRS and RTK).

These commercial networks provide an important extension of the scientific ones, which are actually constituted of about 80 public CGPSs managed by several Italian and European scientific institutions: the Italian GPS Fiducial Network [IGFN - ASI, Vespe *et al*. (2000)], RING - INGV (Selvaggi *et al*., 2006; Devoti *et al*., 2008), the European EUREF network (Bruyninx, 2005), Frednet (Zuliani *et al*., 2002), LabTopo (Fastellini *et al*., 2008), and other research institutions (Cenni *et al*., 2008).

The daily observations provided by 185 CGPS (Fig. 1) stations are analyzed to estimate the actual kinematic pattern in the northern and central part of the Italian peninsula. In particular, attention is focalized on the vertical movements induced by the complex subsidence phenomena of the Po Plain, a sedimentary basin bounded by two fold-thrusts: the N-NE vergent northern Apennines and the southern Alps ranges (Cremonini and Ricci Lucchi, 1982; Doglioni, 1993). A

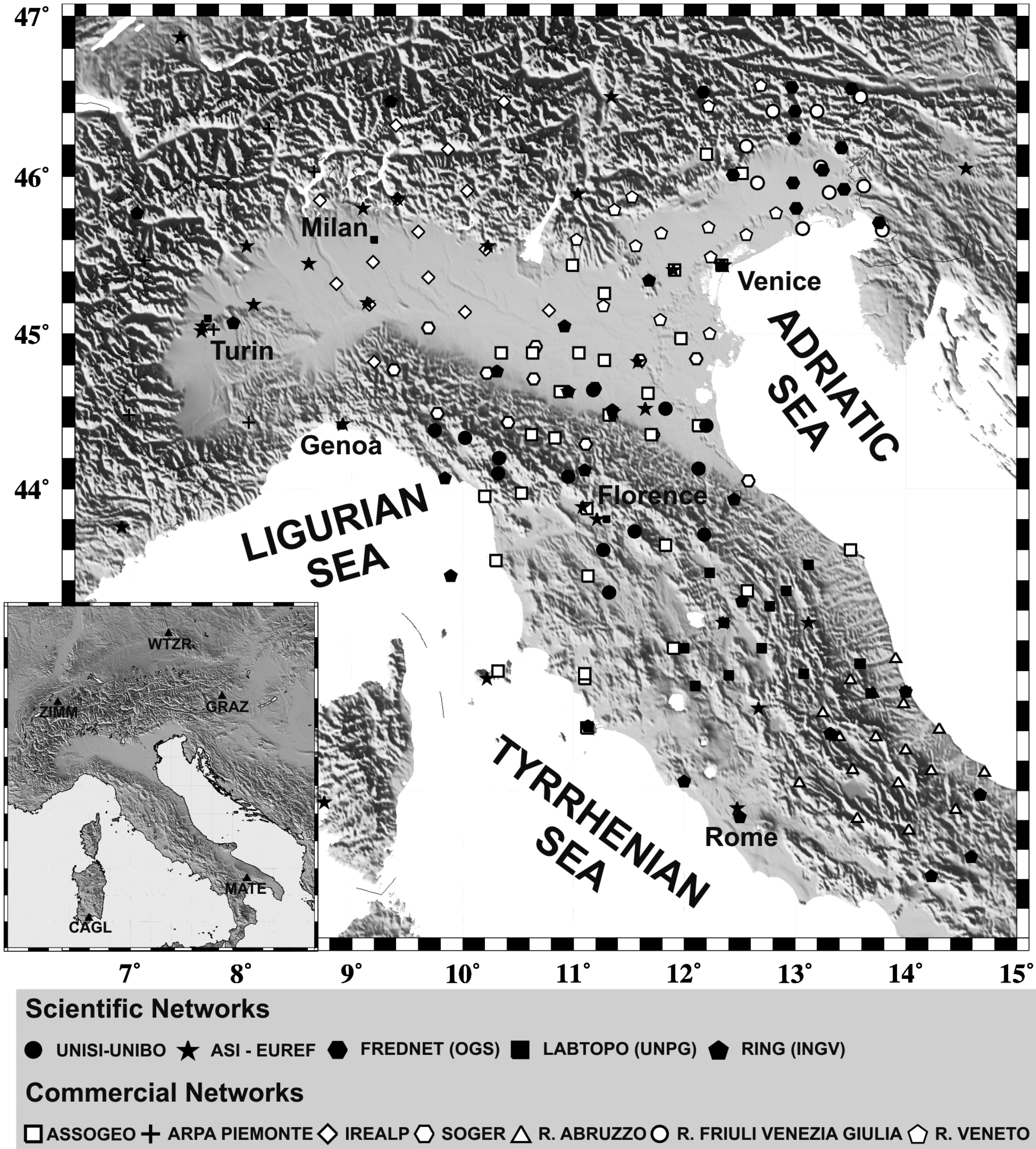

Fig. 1 - Distribution of the CGPS stations analyzed in this study. The solid and open symbols represent, respectively, the scientific and commercial networks. The daily solutions are aligned to the ITRF2005 reference frame using the coordinates and velocities of the sites shown in the inset.

total area of about 38,000 km^2, where a Quaternary sedimentary sequence, composed of alternate sand and clay layers with a maximum thickness of about 2000 m (Dondi *et al.*, 1985) and characterized by a complex multiaquifer freshwater system (Teatini *et al.*, 2006), is affected by a land subsidence of both natural and anthropogenic origin.

A long term natural subsidence is mainly related to deep tectonic and geodynamic movements. Carminati *et al*. (2003) indicate the downflexure of the Adriatic plate, due to its south-westward subduction under the Apennines, as a possible cause of a movement of a maximum rate of 2.5 mm/yr; the possible effects of the tectonic activity of the northern Apennine front on the thrust front buried beneath the Quaternary sediments is thoroughly discussed in Picotti and Pazzaglia (2008). Other authors suggest that the recent deformation pattern of the Apennines belt and Po Plain has been driven by the northward motion of the Adriatic plate (Mantovani *et al*., 2009).

A shorter term component, likely controlled by climatic changes (glaciation cycles), acting on periods of 10^3–10^4 yr, is induced by the melting of Alpine and remote glaciers (Stocchi *et al*., 2005; Stocchi and Spada, 2007).

A further contribution to the natural subsidence, due to the loading and compaction of alluvial deposits, may be estimated in the order of 1 mm/yr (Gianbastiani *et al*., 2007).

The subsidence phenomena has been periodically monitored by leveling measurements since 1897 (Arca and Beretta, 1985); a comparison between the leveling lines from the period 1897-1957 indicates subsidence rates of a few millimetres per year. The total subsidence dramatically increased in the second half of the 20th century, when the economic activities in the region produced a near quadrupling of groundwater extraction for use in industry, agriculture or domestic purposes compared with the previous years (Carminati and Martinelli, 2002). On the basis of field measurements, Salvioni (1957), Caputo *et al*. (1970) and Borgia *et al*. (1982) indicated a maximum subsidence rate of 250 mm/yr in the central part of the Po River delta for the period 1951-1957 and of 180 mm/yr in the following four years, with notable lowering of the piezometric surfaces. In this area, the subsidence rates fell in the following years, in concordance with the progressive reduction of the extraction activities, with the partial closure of artesian wells and the diversification of the water supply. In any case, Caputo *et al*. (1970) estimated that the extraction activities have caused an irregular subsidence ranging from 1 meter to 3.5 meters.

Due to the significant economic impact of this phenomena the vertical movements have been monitored since 1950 (Salvioni, 1957) by means of repeated precise leveling performed by IGMI (Istituto Geografico Militare Italiano), and successively by other local authorities, Companies and Institutions (Caputo *et al*., 1970, 1972; Borgia *et al*., 1982; Arca and Beretta, 1985; Barbarella *et al*., 1990; Bondesan *et al*., 1997). More recently, the GPS technique was used to integrate the conventional leveling by means of episodic and continuous measurements on networks connected with the spirit leveling lines (Bitelli *et al*., 2000). Also the Synthetic Aperture Radar Interferometry (InSAR) was adopted to provide deformation maps of the urbanized areas with high spatial and temporal resolution (Strozzi *et al*., 2000; Stramondo *et al*., 2007; Zerbini *et al*., 2007).

The more recent data set, collected by the regional authorities, indicates that the subsidence in the last years of the 20th century was in some areas at least an order of magnitude higher than that produced by geodynamic and geological natural processes; the maximum subsidence rates (up to 60–80 mm/yr) occurred in two regions: the Po delta, east of Rovigo, and the area north of Bologna. These areas are separated by low subsidence (10 mm/yr) in the form of a "saddle" centered around the town of Ferrara (Carminati and Martinelli, 2002), where, after the application of careful policies concerning anthropogenic subsidence reduction, a rate, at level, of about 3 mm/yr or less has been measured (Bonsignore, 2008).

Along the coastline, human activity for pumping water and gas from underground reservoirs still creates many problems in inhabited areas located a few meters above sea level, which are continuously subject to dangerous modifications, resulting in frequent flooding events. One clear example is the historical town of Venice, which lies in a barrier island lagoon system just north of the Po delta, and is regularly swamped by high tides and floods. Land subsidence, both natural and anthropogenic, and northern Adriatic Sea eustasy have caused 23 cm of relative land subsidence referred to the mean sea level over the last 100 years (Tosi *et al*., 2009). The leveling surveys performed in the year 2000 showed that subsidence is no longer occurring in the central part of the Venetian area and in its industrial zone (Mestre) but it is still going on in the northern and southern lagoon areas and bordering lands (Carbognin *et al*., 2004).

Also small drained portions of the Po Plain, currently below sea level, continue to sink, and demand large-scale investment projects for flooding of rivers and sea defences. Around the metropolitan areas the intense water withdrawal for use in industry and domestic purposes, produces subsidence, which in some cases has recently reached maximum values of 80 mm/yr (Bitelli *et al.*, 2000; Bonsignore, 2008).

The last spirit leveling campaigns performed in 1999 and 2005, and radar data analysis with the PSInSAR technique in the period 2002 - 2006, indicate a widespread further reduction of the subsidence rate in the southern side of the Po Plain area (Emilia Romagna region).

2. GPS data analysis

The available daily observations over the time period of 2001-2008 have been processed using the GAMIT software version 10.35 (Herring *et al*., 2006b). The 185 scientific and commercial CGPS sites were divided into 13 sub-networks (cluster) and analyzed adopting the distributed processing procedure (Dong *et al*., 1998). The double differences phase observation of each cluster were processed assigning tight constraints to the IGS precise ephemeris and the Earth orientation parameters (EOP). High a priori uncertainties were also assigned to the coordinates of each site that is included in the analysis, in order to obtain loose daily solutions for every cluster. The solid Earth tides were estimated by IERS/IGS 2003 model and pole tide corrections were applied according to IERS standards (Dong *et al*., 2002; Herring *et al*., 2006b). The ocean-loading tide effect was modeled by means of the FES2004 tidal model produced at CNES (Lyard *et al*., 2006). The absolute corrections for Phase Center Variation (PCV) were applied to both satellite and terrestrial antennas. The 13 loose daily cluster solutions were combined into a single regional unconstrained solution by GLOBK software (Herring *et al*., 2006a) using the coordinates and velocities of the following six stations: BRAS, CAGL, GRAZ, MATE WTZR and ZIMM (Fig. 1), included in each sub-network. The alignment of the regional daily solutions into the ITRF2005 reference frame (Altamimi *et al*., 2007) was obtained using the coordinates and velocity of five IGS stations (CAGL, GRAZ, MATE, WTZR, ZIMM) by a six parameter Helmert transformation (three rotation and three translation).

The daily time series of the north, east and vertical position coordinates of each site were preliminarily analyzed in order to detect and remove outliers, defined as the data with value or associated uncertainties greater than 3 times the root mean square (rms) of the series. The outliers

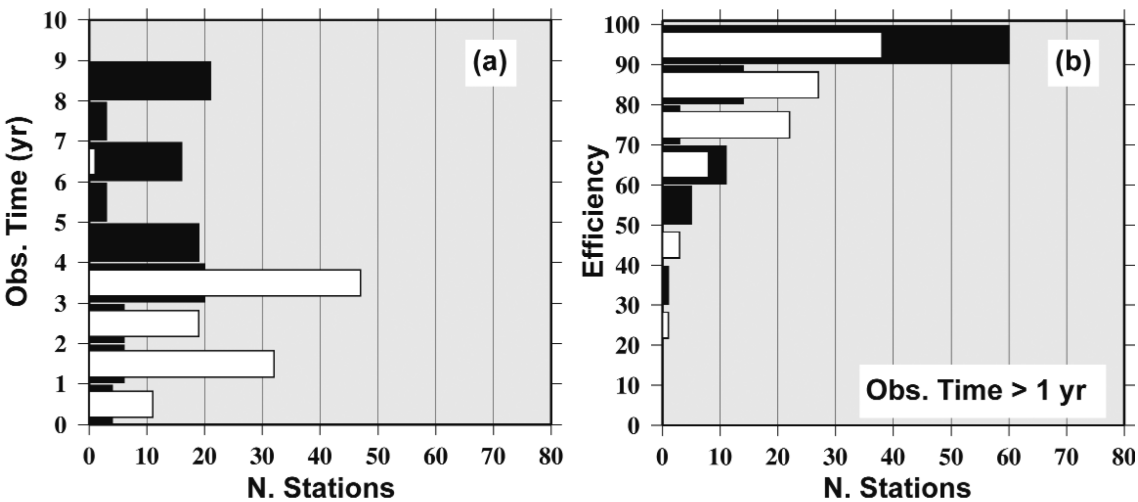

Fig. 2 - Observation time span (a) and efficiency (b) comparison between the scientific stations (black bar) and the commercial sites (white bar).

were identified separately in each coordinate and then removed from all the series.

The cleaned data were analyzed by means of the software "Create and Analyze Time Series" [CATS, Williams (2003, 2008)], using an Maximum Likelihood Estimation (MLE) approach, in order to estimate the linear trend, steps due to earthquakes or equipment changes, annual and semi - annual periodic signals and the amplitude of white noise and coloured noise, in order to correctly estimate the station velocity uncertainties (Nikolaidis, 2002; Williams, 2003, 2008; Teferle *et al*., 2008).

The ITRF2005 velocity values and associated realistic uncertainties of each site with an observation period larger than 1 year are reported in Table 1. As expected, the uncertainties associated to the horizontal components of velocity (north and east) are lower than the values of the vertical ones which ranges between 0.2 mm/yr and 2 mm/yr; a strong correlation between the errors and the time series length is also evident.

One source of noise in geodetic signals is a random motion occurring within the connection of the GPS antenna to the ground. This noise is present in all types of GPS installations; the building protocol adopted to realize a scientific station tries to minimize the influence of this component in the observation, using complex and expensive supports to assure antenna stability (i.e., deep drilled braced monuments or reinforced concrete piers anchored in bedrock or on top of old and stable buildings where bedrock is not exposed or within a few meters of the surface). Otherwise the commercial CGPSs are generally realized using simple and economic systems for antenna installation (i.e., steel bar anchored to the roof of a building or iron/steel pipes solidly connected to the supporting walls with fixing screws or steel poles inserted and cemented into the foundation walls). Moreover, the choice of sites not affected by the presence of interference from radio frequency sources for CGPS installation is demanded by scientific agencies while no defined criteria are adopted by the commercial ones.

Table 1 - ITRF2005 GPS velocities and associated uncertainties (mm/yr) of sites with an observation time span greater than one year: four characters site code, observation time interval *T* (year) and station coordinates are listed. The stations belonging to the scientific networks are highlighted with bold characters. In the fifth column (M), the agencies managing the stations are listed : A = Assogeo, AP = Arpa Piemonte, E = EUREF; F= Frednet, I = Italian GPS Fiducial Network, L = LabTopo, BS = University of Bologna and Siena, R = RING-INGV, S = Soger, RA = Regione Abruzzo, RF = Regione Friuli Venezia Giulia, RL = Regione Lombardia (IREALP), RV = Regione Veneto. The rate uncertainties are estimated taking into account the significant effects of coloured noise and the length of the time series (Williams *et al*., 2004).

CODE	T	Lon. E (°)	Lat. N (°)	M	V_{North}	V_{East}	$V_{Vertical}$
ACOM	**5.5**	**13.51**	**46.55**	**F**	**15.9 ± 0.1**	**21.0 ± 0.3**	**1.2 ± 0.6**
AFAL	**5.5**	**12.17**	**46.53**	**F**	**16.0 ± 0.1**	**20.1 ± 0.3**	**2.7 ± 0.5**
AJAC	**8.0**	**8.76**	**41.93**	**E**	**16.0 ± 0.1**	**20.6 ± 0.1**	**1.1 ± 0.2**
ALRA	1.9	14.03	41.73	RA	22.0 ± 1.4	20.1 ± 1.6	0.1 ± 4.3
AN01	2.7	13.50	43.60	A	17.8 ± 0.3	22.6 ± 0.2	0.4 ± 1.0
AQRA	2.5	13.37	42.37	RA	16.6 ± 0.6	20.0 ± 0.6	0.3 ± 1.9
AQUI	**8.0**	**13.35**	**42.37**	**I**	**17.5 ± 0.1**	**21.1 ± 0.7**	**0.5 ± 0.4**
AR01	2.7	11.84	43.65	A	17.3 ± 0.3	21.3 ± 0.3	-1.5 ± 2.0
ATRA	1.9	14.01	42.55	RA	18.2 ± 1	22.5 ± 0.9	-0.2 ± 2.7
BATE	**5.5**	**12.19**	**43.71**	**BS**	**17.2 ± 0.2**	**21.4 ± 0.2**	**2.1 ± 0.7**
BIEL	**4.9**	**8.05**	**45.56**	**I**	**15.6 ± 0.1**	**19.7 ± 0.5**	**1.6 ± 0.6**
BLRA	2.0	13.56	41.81	RA	19.5 ± 1.4	21.9 ± 1.7	2.9 ± 4.2
BO01	2.7	11.32	44.49	A	16.5 ± 0.6	23.0 ± 0.7	-3.9 ± 1.7
BO03	2.7	11.67	44.62	A	17.8 ± 0.2	22.1 ± 0.2	-4.9 ± 0.9
BOLG	**3.8**	**11.36**	**44.50**	**E**	**20.3 ± 0.4**	**21.3 ± 0.6**	**-3.2 ± 1.9**
BORM	3.0	10.36	46.47	RL	15.9 ± 0.8	19.1 ± 0.9	-0.9 ± 2.5
BRAS	**8.0**	**11.11**	**44.12**	**R**	**17.0 ± 0.1**	**21.3 ± 0.1**	**2.3 ± 0.4**
BREA	3.0	10.23	45.56	RL	16.6 ± 0.4	20.6 ± 0.3	0.3 ± 1.0
BRIX	**4.4**	**10.23**	**45.56**	**I**	**16.0 ± 0.2**	**20.2 ± 0.2**	**1.7 ± 0.5**
BSSO	**3.0**	**14.59**	**41.55**	**R**	**18.1 ± 0.2**	**21.8 ± 0.2**	**2.7 ± 1.0**
BZRG	**6.6**	**11.34**	**46.5**	**E**	**16.5 ± 0.3**	**20.0 ± 0.2**	**2.6 ± 0.6**
CAGL	**8.0**	**8.97**	**39.14**	**E**	**16.0 ± 0.1**	**21.6 ± 0.1**	**0.6 ± 0.2**
CAME	**8.0**	**13.12**	**43.11**	**E**	**18.1 ± 0.3**	**23.1 ± 0.3**	**0.2 ± 1.4**
CANV	**4.6**	**12.44**	**46.01**	**F**	**17.4 ± 0.3**	**20.1 ± 0.3**	**1.3 ± 0.4**
CARG	**5.1**	**10.32**	**44.11**	**BS**	**16.3 ± 0.2**	**20.8 ± 0.2**	**1.5 ± 1.1**
CAST	1.8	10.41	44.43	S	17.8 ± 0.9	21.3 ± 0.1	1.1 ± 1.1
CDRA	2.1	13.72	42.37	RA	19.6 ± 1	21.1 ± 0.8	0.0 ± 2.7
CHIA	1.1	9.40	46.32	RL	15.9 ± 3	21.4 ± 3	0.7 ± 9.1
CMRA	2.5	14.46	41.87	RA	19.7 ± 0.9	19.6 ± 0.8	1.4 ± 2.1
CODI	1.4	12.11	44.84	S	16.7 ± 0.3	21.2 ± 0.3	-1.7 ± 1.1
CODR	**1.7**	**12.98**	**45.96**	**F**	**16.6 ± 0.7**	**21.1 ± 0.4**	**2.2 ± 1.0**
COLL	1.4	10.22	44.75	S	17.6 ± 0.4	21.9 ± 0.1	-2.2 ± 0.6
COMO	**6.7**	**9.10**	**45.8**	**I**	**15.7 ± 0.2**	**20.0 ± 0.2**	**1.3 ± 0.5**
CRE1	**1.6**	**8.11**	**45.19**	**I**	**15.4 ± 0.5**	**20.9 ± 0.5**	**-2.3 ± 1.6**
CREA	3.0	9.69	45.35	RL	16.9 ± 0.5	20.4 ± 0.3	-0.1 ± 1
CREM	2.8	10.00	45.15	RL	17.2 ± 0.4	20.7 ± 0.3	0.9 ± 0.9
DALM	3.0	9.60	45.65	RL	15.9 ± 0.3	20.7 ± 0.3	2.0 ± 0.9
ELBA	**7.9**	**10.21**	**42.75**	**E**	**16.3 ± 0.1**	**20.4 ± 0.1**	**0.6 ± 0.4**

Table 1 - continued.

CODE	T	Lon. E (°)	Lat. N (°)	M	V_{North}	V_{East}	$V_{Vertical}$
CREM	2.8	10.00	45.15	RL	17.2 ± 0.4	20.7 ± 0.3	0.9 ± 0.9
DALM	3.0	9.60	45.65	RL	15.9 ± 0.3	20.7 ± 0.3	2.0 ± 0.9
ELBA	**7.9**	**10.21**	**42.75**	**E**	**16.3 ± 0.1**	**20.4 ± 0.1**	**0.6 ± 0.4**
FE01	2.4	11.98	44.97	A	16.4 ± 0.3	22.2 ± 0.2	-5.6 ± 0.9
FERR	1.5	11.60	44.83	S	17.7 ± 0.1	21.2 ± 0.1	0.1 ± 1.0
FRES	**2.3**	**14.67**	**41.97**	**R**	**17.6 ± 0.5**	**22.9 ± 0.3**	**2.0 ± 1.0**
FRRA	2.5	14.29	42.42	RA	18.2 ± 0.6	22.6 ± 0.6	1.5 ± 1.7
FUSE	**1.3**	**13.00**	**46.41**	**F**	**15.4 ± 0.8**	**21.1 ± 0.8**	**0.1 ± 1.7**
GAVI	3.0	8.70	45.85	RL	15.4 ± 0.6	20.3 ± 0.4	0.5 ± 1.0
GENO	**8.0**	**8.92**	**44.42**	**I**	**15.7 ± 0.1**	**20.6 ± 0.1**	**0.8 ± 0.3**
GR01	2.7	11.12	42.43	A	16.3 ± 0.7	20.9 ± 0.2	-3.5 ± 2.9
GRAS	**8.0**	**6.92**	**43.75**	**E**	**16.1 ± 0.2**	**19.8 ± 0.2**	**2.3 ± 0.4**
GRAZ	**8.0**	**15.49**	**47.07**	**E**	**15.6 ± 0.1**	**21.7 ± 0.1**	**0.9 ± 0.3**
GROG	**2.4**	**9.89**	**43.43**	**R**	**16.2 ± 0.3**	**20.9 ± 0.3**	**-1.4 ± 0.9**
GSR1	**7.9**	**14.54**	**46.05**	**E**	**17.1 ± 0.2**	**20.7 ± 0.3**	**0.9 ± 0.6**
GUAS	1.9	10.66	44.92	S	17.2 ± 0.1	21.2 ± 0.3	-4.0 ± 0.6
IENG	**5.1**	**7.64**	**45.02**	**E**	**15.6 ± 0.4**	**20.4 ± 0.2**	**2.0 ± 0.3**
IGMI	**2.1**	**11.21**	**43.8**	**E**	**17.6 ± 0.8**	**21.6 ± 0.1**	**1.5 ± 1.5**
IM01	2.7	11.71	44.35	A	19.1 ± 0.1	22.4 ± 0.2	-0.1 ± 1.1
INGR	**6.9**	**12.51**	**41.83**	**R**	**17.1 ± 0.2**	**20.7 ± 0.2**	**0.8 ± 0.5**
ITFA	**3.0**	**12.93**	**43.34**	**L**	**18.4 ± 0.1**	**23.1 ± 0.2**	**0.0 ± 0.6**
ITGT	**4.0**	**12.78**	**43.23**	**L**	**18.3 ± 0.2**	**22.7 ± 0.5**	**2.2 ± 1.4**
ITIM	1.9	11.72	44.35	S	18.8 ± 0.5	22.7 ± 0.5	0.8 ± 1.0
ITRA	**3.0**	**14.00**	**42.66**	**L**	**18.7 ± 0.5**	**22.4 ± 0.4**	**2.2 ± 2.1**
JOAN	**1.5**	**13.42**	**46.18**	**F**	**16.4 ± 0.5**	**20.5 ± 0.4**	**-1.1 ± 1.1**
LAGA	**1.8**	**10.95**	**44.08**	**BS**	**18.5 ± 2.0**	**21.4 ± 0.9**	**-1.1 ± 4.1**
LASP	**2.5**	**9.84**	**44.07**	**R**	**16.3 ± 0.4**	**21.1 ± 0.1**	**-0.6 ± 0.7**
LEC1	**5.5**	**9.41**	**45.86**	**I**	**16.0 ± 0.1**	**19.7 ± 0.1**	**0.8 ± 3.9**
LECC	3.0	9.41	45.86	RL	15.7 ± 0.4	19.8 ± 0.4	1.2 ± 1.2
LI01	2.7	10.32	42.81	A	16.1 ± 0.2	20.7 ± 0.1	-1.5 ± 1.0
LU02	2.7	10.23	43.96	A	15.3 ± 0.7	21.4 ± 0.5	-4.3 ± 1.7
LU03	2.7	10.54	43.98	A	17.4 ± 0.4	21.8 ± 0.3	-2.5 ± 1.1
M0SE	**4.2**	**12.49**	**41.89**	**E**	**16.9 ± 0.3**	**20.9 ± 0.3**	**1.5 ± 0.8**
MANT	3.0	10.79	45.16	RL	16.9 ± 0.4	20.7 ± 0.3	0.5 ± 0.9
MAON	**2.7**	**11.13**	**42.43**	**R**	**16.3 ± 0.3**	**20.5 ± 0.1**	**0.3 ± 1.0**
MATE	**8.0**	**16.70**	**40.65**	**E**	**19.2 ± 0.1**	**22.9 ± 0.1**	**0.9 ± 0.2**
MDEA	**3.9**	**13.44**	**45.92**	**F**	**17.9 ± 0.6**	**20.3 ± 0.6**	**0.2 ± 0.8**
MEDI	**8.0**	**11.65**	**44.52**	**E**	**17.5 ± 0.2**	**21.8 ± 0.5**	**-0.5 ± 0.4**
MILA	3.0	9.23	45.48	RL	16.8 ± 0.3	20 ± 0.3	-0.7 ± 0.8
MO01	2.7	10.90	44.64	A	19.9 ± 0.3	19.2 ± 0.3	-15.7 ± 0.8
MO02	5.7	10.83	44.34	A	18.4 ± 0.2	22.2 ± 0.2	0.1 ± 1.2
MO03	2.7	10.62	44.36	A	18.8 ± 0.1	21.8 ± 0.3	0.3 ± 1.4
MO04	1.8	11.07	44.9	A	20.0 ± 0.9	23.0 ± 0.4	-1.0 ± 1.1
MO05	2.7	11.29	44.84	A	17.2 ± 0.7	21.2 ± 0.3	-1.9 ± 1.2

Table 1 - continued.

CODE	T	Lon. E (°)	Lat. N (°)	**M**	V_{North}	V_{East}	$V_{Vertical}$
MODE	**2.1**	**10.95**	**44.63**	**E**	**19.5 ± 0.5**	**20.8 ± 0.3**	**-12.5 ± 1.1**
MOIE	**3.8**	**13.12**	**43.5**	**L**	**18.2 ± 0.3**	**22.4 ± 1.9**	**2.1 ± 2.4**
MONC	**2.7**	**7.93**	**45.07**	**R**	**15.4 ± 0.2**	**20.8 ± 0.2**	**0.8 ± 0.9**
MOPS	**1.7**	**10.95**	**44.63**	**E**	**19.1 ± 0.4**	**19.3 ± 0.1**	**-15.1 ± 1.2**
MPRA	**6.0**	**12.99**	**46.24**	**F**	**16.7 ± 0.3**	**20.2 ± 0.2**	**0.9 ± 0.5**
MRGE	**2.3**	**7.06**	**45.77**	**R**	**15.1 ± 0.3**	**19.4 ± 0.3**	**0.5 ± 1.3**
MRRA	2.1	13.92	42.89	RA	18.5 ± 0.6	23.4 ± 0.6	0.2 ± 1.8
MSEL	**4.3**	**11.65**	**44.52**	**E**	**17.9 ± 0.1**	**21.9 ± 0.1**	**0.4 ± 0.5**
MTRA	2.5	13.24	42.53	RA	15.9 ± 0.7	20.1 ± 0.8	0 ± 2.3
MURB	**3.5**	**12.52**	**43.26**	**R**	**14.5 ± 0.6**	**23.9 ± 0.5**	**2.0 ± 0.8**
NOVA	**8.0**	**8.61**	**45.45**	**I**	**16.1 ± 0.1**	**19.9 ± 0.1**	**1.2 ± 0.2**
OCRA	2.1	13.04	42.05	RA	19.6 ± 0.7	23.4 ± 0.7	0.8 ± 2.2
OMBR	**5.5**	**11.56**	**43.73**	**BS**	**17.2 ± 0.3**	**21.1 ± 0.2**	**1.7 ± 0.5**
OVRA	2.1	13.52	42.14	RA	20.4 ± 1.2	21.5 ± 0.9	-0.2 ± 2.6
PADO	**7.1**	**11.90**	**45.41**	**E**	**17.0 ± 0.3**	**20.9 ± 0.2**	**0.8 ± 0.4**
PARM	**2.2**	**10.31**	**44.76**	**R**	**17.7 ± 0.4**	**21.3 ± 0.3**	**-0.4 ± 1.1**
PAVI	**7.5**	**9.14**	**45.2**	**I**	**16.3 ± 0.2**	**20.6 ± 0.3**	**-0.8 ± 0.8**
PBRA	2.5	14.23	42.12	RA	19.8 ± 0.9	22.7 ± 1.1	1.9 ± 2.5
PD01	1.1	11.88	45.42	A	17.4 ± 0.8	20.9 ± 0.6	-5.1 ± 2.3
PERS	1.9	11.19	44.65	S	17.6 ± 0.3	22.6 ± 0.4	-8.0 ± 0.8
PG01	2.2	12.58	43.34	A	18.8 ± 0.5	22.8 ± 0.3	1.1 ± 1.4
PIAC	1.4	9.69	45.04	S	17.2 ± 0.5	20.7 ± 0.2	-0.2 ± 1.1
PO01	2.5	11.12	43.87	A	16.9 ± 0.3	21.4 ± 0.4	1.6 ± 0.9
PORA	1.8	10.11	45.89	RL	13.5 ± 1.4	22.6 ± 1.1	1.4 ± 2.7
PR01	2.7	10.36	44.89	A	17.1 ± 0.2	20.9 ± 0.1	-2.4 ± 0.9
PRAT	**8.0**	**11.10**	**43.89**	**E**	**17.3 ± 0.1**	**21.3 ± 0.1**	**0.8 ± 0.3**
PVIA	**2.9**	**9.14**	**45.20**	**RL**	**16.4 ± 0.4**	**20.7 ± 0.4**	**0.4 ± 0.9**
RAVE	**3.6**	**12.20**	**44.41**	**BS**	**18.8 ± 0.1**	**23.3 ± 0.2**	**-2.1 ± 0.7**
RAVS	1.9	12.19	44.41	S	18.0 ± 0.3	22.7 ± 0.3	-4.7 ± 0.8
RE01	2.7	10.64	44.89	A	16.4 ± 0.2	22.8 ± 0.2	-3.4 ± 0.9
REFO	**2.9**	**12.70**	**42.96**	**L**	**17.9 ± 0.3**	**22.7 ± 0.3**	**1.9 ± 0.9**
REMO	**2.3**	**12.23**	**43.45**	**L**	**18.4 ± 0.6**	**21.5 ± 0.5**	**0.2 ± 1.4**
RENO	**3.0**	**13.09**	**42.79**	**L**	**17.5 ± 0.5**	**22.5 ± 0.2**	**0.1 ± 1.5**
REPI	**3.1**	**12.00**	**42.95**	**L**	**17.7 ± 0.2**	**21.1 ± 0.2**	**1.5 ± 0.9**
RETO	**3.1**	**12.41**	**42.78**	**L**	**17.4 ± 0.3**	**21.3 ± 1.2**	**2.9 ± 1.9**
ROGA	**5.3**	**10.34**	**44.21**	**BS**	**16.2 ± 0.1**	**20.4 ± 0.1**	**0.5 ± 0.5**
ROVE	**2.7**	**11.04**	**45.89**	**I**	**16.5 ± 0.5**	**20.9 ± 0.5**	**0.7 ± 1.1**
RSMN	**3.1**	**12.45**	**43.93**	**R**	**18.1 ± 0.4**	**22.8 ± 0.4**	**1.5 ± 1.6**
RSTO	**6.0**	**14.00**	**42.66**	**R**	**17.7 ± 0.2**	**23.1 ± 0.2**	**0.8 ± 0.3**
SBPO	**2.6**	**10.92**	**45.05**	**R**	**16.7 ± 0.3**	**20.5 ± 0.2**	**-0.3 ± 0.8**
SCRA	2.1	14.00	42.27	RA	18.3 ± 0.9	22.6 ± 1	1.8 ± 2.6
SGIP	**3.9**	**11.18**	**44.64**	**R**	**17.2 ± 0.3**	**22.7 ± 0.3**	**-7.0 ± 0.8**
SI01	2.7	11.90	42.96	A	17.4 ± 0.4	20.8 ± 0.2	0.8 ± 0.3
SI02	2.7	11.14	43.47	A	16.8 ± 0.2	20.9 ± 0.3	1.5 ± 0.7

Table 1 - continued.

CODE	T	Lon. E (°)	Lat. N (°)	M	V_{North}	V_{East}	$V_{Vertical}$
SIEN	**5.0**	**11.34**	**43.31**	**BS**	**16.4 ± 0.1**	**20.5 ± 0.2**	**1.5 ± 0.7**
SMRA	2.5	13.92	42.05	RA	18.4 ± 0.6	22.4 ± 0.6	-3.5 ± 2.2
SOND	2.5	9.85	46.17	RL	17.2 ± 1.4	19.1 ± 1.1	1.1 ± 3.7
STUE	**2.2**	**9.35**	**46.47**	**R**	**20.1 ± 1.0**	**21.9 ± 0.9**	**-0.5 ± 1.5**
TARO	1.4	9.77	44.49	S	16.3 ± 0.7	21.6 ± 0.4	-1.3 ± 2.3
TEOL	**3.7**	**11.68**	**45.34**	**R**	**17.5 ± 0.2**	**20.9 ± 0.2**	**0.6 ± 0.6**
TOLF	**3.7**	**12,00**	**42.06**	**R**	**17.4 ± 0.3**	**21.5 ± 2.7**	**0.9 ± 0.6**
TORI	**8.0**	**7.66**	**45.06**	**E**	**15.8 ± 0.1**	**20.0 ± 0.2**	**2.3 ± 0.4**
TREC	**5.1**	**10.02**	**44.34**	**BS**	**16.6 ± 0.2**	**20.6 ± 0.2**	**1.4 ± 0.6**
TRIE	**5.9**	**13.76**	**45.71**	**F**	**17.3 ± 0.2**	**20.7 ± 1.3**	**1.2 ± 0.5**
TRLU	**5.8**	**11.27**	**43.61**	**BS**	**17.1 ± 0.3**	**21.3 ± 0.2**	**-0.3 ± 0.6**
UDI1	**2.7**	**13.25**	**46.04**	**F**	**17.7 ± 0.6**	**20.5 ± 0.4**	**0.3 ± 2.3**
UNFE	**7.2**	**11.60**	**44.83**	**I**	**17.9 ± 0.2**	**21.3 ± 0.2**	**-1.1 ± 0.7**
UNOV	**4.0**	**12.11**	**42.72**	**L**	**17.2 ± 0.2**	**21.4 ± 0.4**	**2.2 ± 0.9**
UNPG	**8.0**	**12.36**	**43.12**	**E**	**16.2 ± 0.2**	**20.7 ± 0.2**	**1.5 ± 0.5**
UNTR	4.0	12.67	42.56	I	17.3 ± 0.6	21.7 ± 0.5	0.9 ± 1.3
UPG2	**1.9**	**12.36**	**43.12**	**L**	**16.8 ± 0.5**	**21.8 ± 0.6**	**1.7 ± 1.9**
VAGA	**2.8**	**14.23**	**41.42**	**R**	**20.7 ± 3.6**	**23.9 ± 0.5**	**0.2 ± 0.9**
VARZ	3.0	9.20	44.82	RL	16.4 ± 0.4	20.7 ± 0.4	1.3 ± 1.0
VCRA	2.5	13.50	42.74	RA	18.1 ± 0.9	21.9 ± 1.0	-0.4 ± 3.0
VE01	1.1	12.33	45.44	A	17.1 ± 1.0	21.2 ± 0.2	-2.3 ± 2.1
VEAR	**2.7**	**12.36**	**45.44**	**E**	**18.1 ± 0.1**	**21.0 ± 0.4**	**-1.9 ± 1.4**
VENE	**6.6**	**12.33**	**45.44**	**I**	**17.0 ± 0.4**	**20.9 ± 0.2**	**0.3 ± 0.4**
VERG	1.3	11.11	44.29	S	17.1 ± 0.2	23.4 ± 0.6	0.3 ± 2.0
VIGE	2.8	8.86	45.31	RL	16.4 ± 0.3	20.4 ± 0.4	0.7 ± 1.0
VTRA	2.5	14.71	42.11	RA	18.2 ± 0.6	22.9 ± 0.6	0.4 ± 2.1
WTZR	**8.0**	**12.88**	**49.14**	**E**	**15.7 ± 0.2**	**20.0 ± 0.2**	**0.9 ± 0.3**
ZERI	**3.3**	**9.75**	**44.39**	**BS**	**16.3 ± 0.7**	**20.7 ± 0.3**	**1.0 ± 0.8**
ZIMM	**8.0**	**7.47**	**46.88**	**E**	**16.4 ± 0.1**	**19.3 ± 0.1**	**2.5 ± 0.2**
ZOUF	**5.6**	**12.97**	**46.56**	**F**	**16.0 ± 0.4**	**20.6 ± 0.3**	**2.0 ± 0.9**

For these reasons, the noise level affecting the coordinate time series of commercial and scientific CGPSs were analyzed and compared in order to evaluate if the commercial observations can be used for scientific purposes.

Looking at the measurement time spans, it is to be noted that commercial stations operated on shorter periods (Fig. 2a). For each station, the efficiency was computed as the ratio between the number of usable data and the total available data. The lower apparent efficiency (Fig. 2b) of young commercial stations can be due to the experimental phase preceding their standard and regular functionality, as suggested in other studies (e.g., Baldi *et al*., 2009).

A simple quality check for the commercial data can be performed comparing the post-fit weighted RMS (WRMS) of the daily coordinate time series with ones obtained with scientific

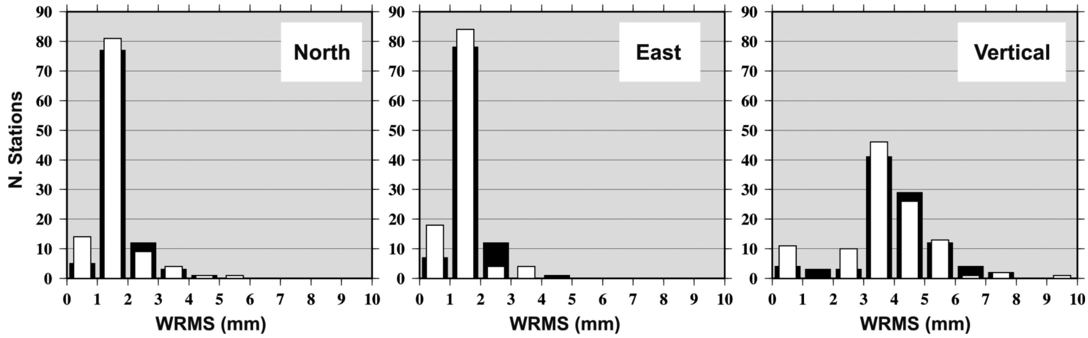

Fig. 3 - Distribution of WRMS values obtained by processing the observation of commercial sites (white bar) and the data of scientific stations (black bar). Only the stations with a time observation span greater than one year are considered in the analysis.

observations; Fig. 3 does not show significant differences. The average WRMS of horizontal coordinates is about 1-2 mm and something more (3-4 mm) for the vertical one, both in the scientific and commercial station sets. Concerning the time-wise correlated signals, the dominant model was estimated as white plus flicker noises, with similar magnitude for commercial and scientific stations, consistent with previously published results (Baldi *et al*., 2009).

This data analysis confirms the results obtained by other authors (Beavan, 2005; D'Agostino *et al*., 2008; Baldi *et al*., 2009), demonstrating that in many cases the simple commercial antenna monumentation does not prevent the quality of solutions (coordinate time series). All this evidence encourages possible and efficient integrations of scientific and commercial CGPSs, allowing a more detailed analysis of crustal movements without degrading the accuracy of the solutions.

3. Results and discussion

The present day velocity field in central-northern Italy was obtained by processing data from 156 commercial and scientific stations with at least a 1 yr observation time span and characterized by an efficiency greater than 50% (Fig. 4). The interpretation of GPS results requires great caution, especially if the velocity values are estimated analyzing short time coordinate series. In particular, the time series may be largely affected by several errors not completely modeled and removed, mainly due to roughly modeled tropospheric delays, site and environmental loading effects (air pressure, sea level, water storages), inconsistencies in the reference frame and satellite ephemerides, antenna PCV. For this reason the choice of a minimum observation time of about 2.5 yrs is suggested by some authors (e.g., Blewitt and Lavallè, 2002) to avoid wrong interpretations of the results. In this study, the spatial consistency without significant differences in the horizontal kinematic pattern (Fig. 4) and in the vertical velocity field (Fig. 5), obtained including "old" (observation time span $T \geq 2.5$ yr) and "young" ($T < 2.5$ yr) sites (Baldi *et al*., 2009) encourages us to include the last in the following discussion.

The velocity values are sampled at irregularly spaced points, but they are representative of

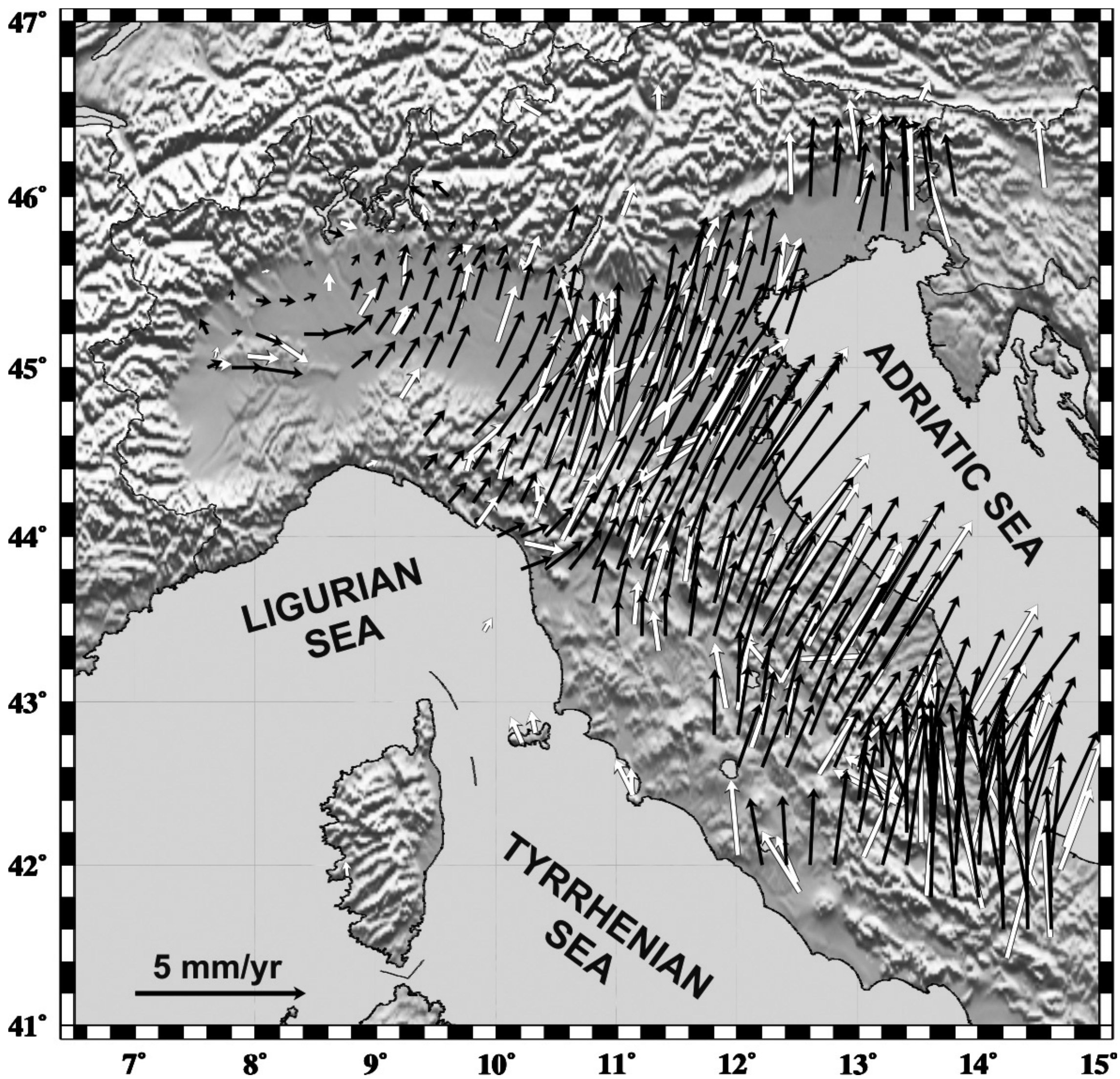

Fig. 4 - Residual horizontal kinematic pattern in the northern-central Italian region. Residual velocities are computed with respect to a fixed Eurasian frame, modeled by an absolute Euler pole located at 56.330 °N, -95.979 °E with a rotation velocity w = 0.261°/Myr (Altamimi *et al*., 2007). Empty arrows indicate the geodetic velocity estimated using the sites with an observation time span greater than 1 yr. Solid arrows represent the interpolated velocity estimated over a regular grid with nodes spaced of 0.2° in latitude and longitude, using a weighted least-square procedure with smoothing parameter of 30 km (Shen *et al*., 1996).

continuous phenomena; in order to minimize the local effects on a possible regional kinematic pattern, an interpolation approach was applied in order to estimate the velocity field on a regular grid: a weighted least-square procedure with a distance-decaying parameter D which takes into account the distances between the grid node and GPS stations was adopted (Shen *et al*., 1996; Teza *et al*., 2008). The networks with an approximately uniform distribution of the stations are the optimal employment for this method. In order to avoid the computation of the kinematic

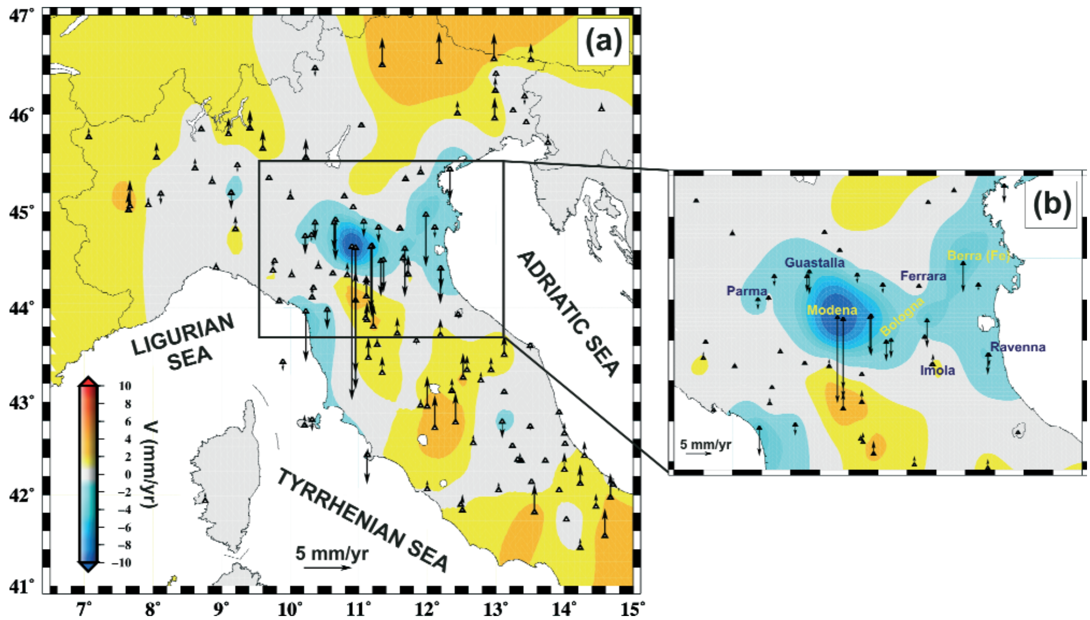

Fig. 5 - a) Vertical velocities (black arrows) and contour map obtained considering the stations with an observation time span longer than one year. b) Vertical kinematic pattern in the eastern Po Plain area.

pattern characterised by a sparse distribution of stations, we have included a simple test in the interpolation procedure, consisting in the computation of the number of stations included in an area of radius *D* around the node; the interpolated velocity values are evaluated only if in this area almost 3 GPS sites are included.

The horizontal interpolated velocity field, computed with respect to a fixed Eurasian frame, indicates that the outer part of the Apennine chain, from the eastern Latium-Abruzzi platform to the outermost thrust sheet of the northern Apennines buried under the Po Valley sedimentary cover, moves significantly faster than the adjacent structures (Fig. 4), characterized by relatively low velocity values (< 2 mm/yr). It can be noted that the faster sectors correspond fairly well to the outer Apennine units that have been characterized by higher mobility and uplift since the middle Pleistocene in connection with the kinematics of the Adriatic plate (Mantovani *et al*., 2009, 2010).

The vertical kinematic pattern in the northern-central Italian region is shown in Fig. 5, and obtained using the sites with an observation time span greater than 1 yr. The interpolation pattern has been estimated using the kriging geostatistical method over a regular spaced grid.

Fig. 5a shows that the sites located in the Alps and Apennine domains are characterized by a low uplift velocity, while two areas are affected by subsidence phenomena: the Po Plain and the western sector of the Arno Plain.

The rate of CGPS located in the Alps area are of the order of a few millimeters per year, in agreement with previous estimates from repeated leveling in the last century; several studies (Gubler *et al*., 1981; Arca and Beretta, 1985; Kahle *et al*., 1997; Persaud and Pfiffner, 2004) put in evidence an increment of crustal uplift from the foreland to the rear of the central-western part

Table 2 - Comparison between the vertical GPS velocities measured in this study and the values estimated in the central Po Plain area using other techniques. LL indicates the results obtained analyzing the 1999 to 2005 leveling campaigns on selected benchmarks located near the CGPS (maximum distance of some hundred meters) and DInSAR indicates the same results inferred by the 2002–2006 radar satellite data. This information is extracted by subsidence monitoring reports of the ARPA – Emilia (ARPA, 2009).

Site	**CGPS**	**LL** (mm/yr)	**DinSAR** (mm/yr)	**GPS** (mm/yr)
Berra (Fe)	FE01		-7	-5.6 ± 0.9
Bologna	BO01	-5		-3.9 ± 1.7
	BOLG	-18		-3.2 ± 1.9
Codigoro (Fe)	CODI	-6	-8	-1.7 ± 1.1
Collecchio (Pr)	COLL		-1	-2.2 ± 0.6
Ferrara	FERR	-3		0.1 ± 1.0
	UNFE	-3		-1.1 ± 0.7
Finale Emilia (Mo)	MO05	-4		-1.9 ± 1.2
Gualtieri (Re)	RE01	-3		-3.4 ± 0.9
Guastalla (Re)	GUAS		-1	-4.0 ± 0.6
Imola (Bo)	IM01		-3	-0.1 ± 1.1
	ITIM		-3.6	0.8 ± 1.0
	MEDI		-5	-0.5 ± 0.4
Medicina (Bo)	MSEL		-5	0.4 ± 0.5
Mirandola (Mo)	MO04		-2	-1.0 ± 1.1
Modena	MODE	-2		-12.5 ± 1.1
	MOPS	-2		-15.1 ± 1.2
	MO01	-3		-15.7 ± 0.8
Molinella (Bo)	BO03	-6		-4.9 ± 0.9
Parma	PARM		-1	-0.4 ± 1.1
Piacenza PIAC	PIAC		0	-0.2 ± 1.1
Ravenna	RAVE	-6		-2.1 ± 0.7
	RAVS	-5		-4.7 ± 0.8
San Giovanni in	PERS			-8.0 ± 0.8
Persicelo (Bo)	SGIP	-7		-7.0 ± 0.8

of the Alps, where actual rates of movement range from 2-3 mm/yr to 1 mm/yr (Schlatter *et al.*, 2005). The available results from regional and local GPS networks (Pinato Gabrieli *et al*., 2006; Haslinger *et al*., 2007) show a significant uplift rate of a few mm/yr also in a large part of the south-eastern Alps. At present, the Alps' uplift is attributed to the combined effects of crustal processes, isostatic response to unloading of the Alpine crust after the removal of the Pleistocene ice sheet, flexural response to climate-driven denudation (Schlunegger and Hinderer, 2001; Champagnac *et al*., 2009), and rapid glacier shrinkage (Barletta *et al*., 2006).

The observed uplift of the northern Apennines, an active orogenic belt affected by a moderate seismicity, is of the order of 1-2 mm/yr. The deformation of the chain is assumed to be mainly related to long term tectonic processes, as reported by geological and geomorphological studies (Argnani *et al*., 2003; Picotti and Pazzaglia, 2008): the evolution of the northern Apennines in the last 1.0 Ma is characterized by a mean uplift of about 1 mm/yr. The repeated leveling surveys executed by the Istituto Geografico Militare Italiano (IGMI) over 129 years, along the lines across the chain from the Tyrrhenian to the Adriatic side of the peninsula, provided maximum uplift rates in the range 1-3 mm/yr (D'Anastasio *et al*., 2006), with the assumption that most of the Tyrrhenian side of the central-northern Apennines is essentially stable (Bordoni and Valensise, 1998). The uplift rate is also confirmed by the information from the GPS data processing of a dense network, especially designed to measure both the sub-regional and near-field strain rates across the main seismogenic structures and faults of the central Apennines (Anzidei *et al*., 2005; Pesci *et al*., 2009), extending across southern Umbria, Abruzzi and the southern Latium regions, from the Tyrrhenian to the Adriatic Sea.

On the Tyrrhenian margin of the Apennines the two GPS sites (LU02 and LU03) located in the western sector of the Arno Plain show significant subsidence rates of about some mm/yr, and confirm the vertical movement estimated integrating Satellite Radar Interferometry and leveling surveys. The subsidence appears to be related to the withdrawal of groundwater over the last two decades, which caused a drop of the water table (Disperati *et al*., 2005), even if also a long term vertical rate of the same amount is deduced from geological and geophysical observations by some authors (Carminati and Di Donato, 1999; Antonioli and Silenzi, 2000; Cantini *et al*., 2001).

The comparison between the present day subsiding rates measured at CGPS sites in the Po Plain area (Fig. 5b) and the results obtained previously with different techniques (1999-2005 leveling campaigns and DInSAR analysis in the 2002-2006 time span) is shown in Table 2. Clearly, it was not possible to compare data at the same benchmarks, but points with maximum distance of a few hundred meters were considered (ARPA, 2009). The rates are stable or in some cases are decreasing as a possible consequence of the drastic reduction of water withdrawal. In the city of Ferrara, for example, the vertical rates, computed at the two stations, seem to confirm smaller subsidence effects; it is to be noted that some authors describe the mitigation of anthropogenic-induced subsidence as probably due to the active compressional tectonics along the Mirandola-Ferrara anticlines induced by the Late Pliocene-Quaternary propagation of the Apennine thrust front (Scrocca, 2006; Picotti and Pazzaglia, 2008).

The CGPS located in the eastern part of Ferrara province and in proximity of the Po Delta, where sediments of the Plio-Quaternary series are few thousand meters thick, indicates again the presence of a significant subsidence phenomena (-5.6 mm/yr).

The city of Ravenna is located in the eastern part of the Po Plain, were the succession of deposits of the Quaternary have variable thicknesses ranging between 1500 and 3000 m; the extensive groundwater withdrawals started in the early 1950s and the beginning of gas production from onshore and offshore reservoirs produced a subsidence rate up to 110 mm/yr (Gambolati *et al*., 1991). Forty years ago, after a drastic reduction of water withdrawal as consequence of the economic crisis and the activation of a new aqueduct, the velocity strongly decreased to values lower than 10 mm/yr in the city area and in the industrial zone of Ravenna whereas in the coastal area close to the gas reservoirs a maximum of 10-15 mm/yr was recorded in the first years of the 21^{th} century (Teatini *et al*., 2005). The CGPS in Ravenna and surrounding areas indicate a current subsidence rate of about

3 mm/yr.

The most important towns of the Emilia Romagna region and the most productive industrial areas lie on the Apenninic margin of the Po Valley; in the past, human activities produced strong soil sinking resulting from the overuse of groundwater, with a high spatial variability, due to the different thicknesses of sediments from the foot of the hills to the plain, and the heterogeneity of the subsoil.

The city of Bologna is located in the south-eastern margin of the Po Plain and extends to the edge of the hills, in correspondence with two main geological settings: the edge of the Apennines and the alluvial plain. The InSAR time series analysis throughout the 1992-2000 time span, integrated by historical and recent leveling data, indicated that the subsidence ranged from 2-4 mm/yr in the piedmont zone to 50-60 mm/yr in the plane area where the Pliocene and Quaternary sediments became rapidly thicker. Also in this case, recent measurements (performed in the 2002-2006 time span) show a subsidence reduction, even if most of the industrial zone north of the city was affected by a displacement rate of about 20-30 mm/yr, locally reaching a maximum rate greater than 40 mm/yr. More recently, the CGPS stations (BO01 and BOLG) analyzed in this study and located about 1.5 km from the historical centre, respectively in a west and north-eastern direction, have measured a vertical velocity of about -3 mm/yr, confirming the reduction of the phenomena (see Table 2).

Only in the city of Modena area, placed in the Apenninic margin of the Po Valley, is an increase of the velocity evident. The evolution of the phenomena in this area presents strong variation of velocity, with respect to the supposed mean value of about 3 mm/yr for the last 2000 years, obtained considering the Roman archaeological level, buried under 6 m of alluvial deposit, and confirmed by leveling measurements from 1897 to 1957 (Arca and Beretta, 1985). In the period 1950-1981, a much faster human-induced subsidence was added to the one driven by the natural consolidation and a maximum lowering of 84 cm was observed; successively in the time periods 1981-1985, 1985-1992 and 1985-1999 a mean subsidence of about 10 mm/yr were measured, even if it appears highly differentiated in the town centre and surrounding areas (Artusi *et al*., 2004). Velocity peaks, exceeding 20 mm/yr were observed. The 1999-2005 and 2002-2006 time spans were characterized by quite a lowering of the sinking velocity, probably determined by a modified water supply system. The actual velocity (-15 mm/yr) is similar to the observed value in the time interval 1985-1999 (Bonsignore, 2008).

4. Conclusions

The analysis described in this paper indicates that the low-cost monumentations adopted by the commercial CGPS installed by public and private agencies for real time positioning service do not induce significant differences from the noise characteristics of the position time series with respect to the data collected by scientific GPS stations. This result allowed us to integrate the scientific network with commercial sites distributed in northern-central Italy, significantly reducing the mean station spacing, providing in some areas baselines of the order of a few tens of kilometers.

The observations of 185 CGPSs have been analyzed to investigate the subsidence phenomenon of the Po Plain sedimentary basin and vertical movements of the surrounding areas.

The reduction of costs for monitoring land vertical displacements by CGPS with respect to spirit leveling, and the integrated use of DInSAR and GPS data could offer a powerful tool for investigating the short-term temporal evolution of anthropogenic subsidence, satisfying the increasing need for more reliable predictions of the phenomena that in the Po Plain area is characterized by a high spatial and temporal variability.

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Corresponding author: Nicola Cenni
Dipartimento di Fisica, Università di Bologna
Viale Berti Pichat 8, 40127 Bologna, Italy
Phone: +39 051 2095009; fax: +39 051 2095058; e-mail: nicola.cenni@unibo.it